

# MIXED SOURCES OF Pb IN SEDIMENTARY-ROCK-HOSTED Au DEPOSITS, NORTHERN NEVADA

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## ABSTRACT

Pb isotopic compositions for sulfide minerals (orpiment, realgar, stibnite, marcasite, pyrite and galena) in the sedimentary-rock-hosted, or Carlin-type, Au deposits at Getchell, Betze-Post, and in the Jerritt Canyon Mining District in northern Nevada suggest mixing of distinct Pb sources during their formation. Host rocks for the deposits are principally Paleozoic calcareous miogeoclinal rocks. They are commonly capped by siliciclastic eugeoclinal rocks along structural contacts that constitute the Roberts Mountains thrust system; the eugeoclinal rocks are not common host rocks to gold ore. Stocks of Jurassic, Cretaceous and Eocene age are spatially associated with many deposits but a genetic linkage is not established. In the Betze-Post deposit, pre-main gold ore stage base-metal veins contain Pb derived from the host late Middle Jurassic Goldstrike stock of granodioritic composition. Sulfides deposited during formation of a sedimentary-rock-hosted Au deposit do not show any obvious component of Pb from the host Paleozoic miogeoclinal rocks, but rather shows evidence of mixing of two Pb isotopically distinct fluids. One source is characterized by a large range of  $^{206}\text{Pb}/^{204}\text{Pb}$  (18.5-25.3) with a limited range of  $^{208}\text{Pb}/^{204}\text{Pb}$  (38.1-39.5) indicating low but variable Th/U values. This source resembles the Paleozoic siliciclastic eugeoclinal rocks. The second source was characterized by slightly elevated  $^{207}\text{Pb}/^{204}\text{Pb}$  (>15.75) at relatively low  $^{206}\text{Pb}/^{204}\text{Pb}$  (19-20), and by Th/U values close to 4. This source could have been (1) magmatic, or (2) Late Proterozoic and early Paleozoic sedimentary rocks that are generally unexposed in the vicinity of the deposits but must lie at deeper crustal levels, or (3) still deeper lower or middle crustal rocks. Regardless of the exact nature of this low  $^{206}\text{Pb}/^{204}\text{Pb}$  source, mixing of Pb probably took place close to or at the site or ore deposition in order to maintain isotopic integrity of the two sources. The Pb isotopic evidence for fluid mixing is consistent with mineralogical and geochemical data for the sediment-hosted Au deposits.

## INTRODUCTION

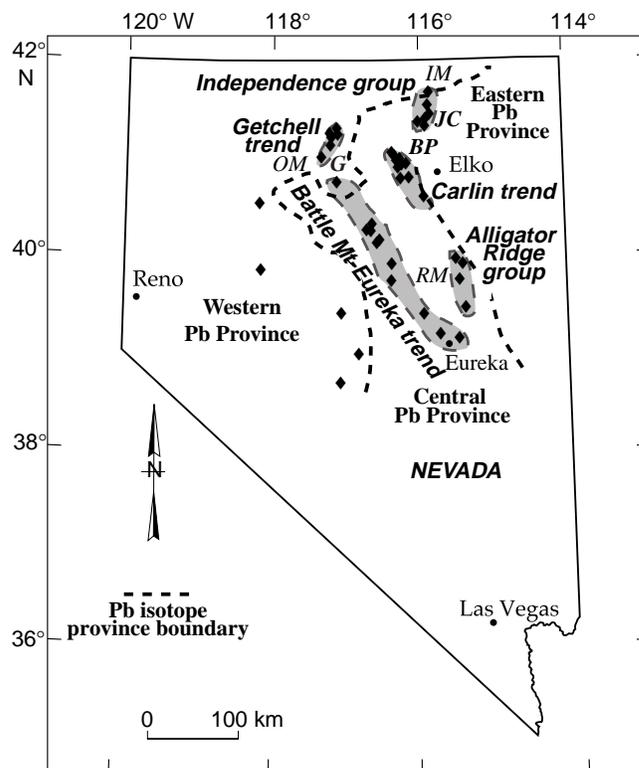
Establishing the source, or sources, of Au in sedimentary

rock-hosted, or Carlin-type, Au deposits is critical to genetic models proposed for their formation (Christensen, 1993). In models appealing to amagmatic sources for the deposits, Au is thought to have been derived from thick sequences of upper Proterozoic and early Paleozoic sedimentary rocks during deep circulation of meteoric water driven by elevated geothermal gradients during Eocene extension and accompanying magmatism (Hofstra, 1995, 1997; Ilchik and Barton, 1997), or as a result of regional metamorphism and dehydration of these same metasedimentary rocks (Seedorf, 1991; Phillips and Powell, 1993; Keuhn and Rose, 1995). Crustal-scale hydrothermal systems are required in these models. In models proposing a magmatic link, Au is derived from a stock, and the deposits are referred to as distal-disseminated Ag-Au deposits (e.g. Sillitoe and Bonham, 1990; Theodore, 1998). A variation on the magmatic model proposes that plutons simply provided the thermal energy necessary for focusing a hydrothermal system (Arehart and others, 1993a; Keuhn and Rose, 1995). In this case, Au was derived largely from sedimentary rocks with little or no contribution from the pluton.

That the sedimentary rock sequence is a reasonable source of Au is supported indirectly by the observation of Titley (1991), who noted an association on a worldwide basis of sedimentary rock-hosted Au deposits with rocks of early Paleozoic or Jurassic and Cretaceous age. Deposition in deep water during times of high sea level and widespread submarine volcanism and hydrothermal activity typify these clastic sequences. In the case of northern Nevada, Young-Mitchell and Titley (1996) further demonstrate a relative enrichment of Au in the early Paleozoic sedimentary rocks. They postulated that Au is detrital and derived from the Precambrian craton to the east. Of interest is their observation that deeper water eugeoclinal rocks deposited farther from the craton are more enriched in Au than carbonate-rich rocks deposited in the shallower water of the miogeocline closer to the craton. Poole and others (1992) also note that eugeoclinal rocks are commonly metalliferous. The relative Au and metal enrichment inherent in the eugeoclinal rocks logically leads to a hypothesis that Au and other metals in sedimentary rock-hosted Au deposits might have been leached out of siliciclastic rock sequences and transported unknown distances as part of large hydrothermal circulation systems (for example, Ilchik and Barton, 1997).

Pb isotopes measured in ore minerals can constrain Pb sources in many types of hydrothermal systems. However, their utility for determining the source of associated metals, such as Au, is also limited by the assumption that Pb was transported and deposited as part of the same hydrothermal fluid. If true, then Pb isotopes serve as a proxy for constraining the source of associated metals. Still another limiting factor is the Pb concentration of a hydrothermal fluid with respect to potential Pb sources during transport and subsequent deposition. If a low Pb concentration characterizes a hydrothermal fluid, then water-rock interactions can change the Pb isotopic compositions of the fluid, hence minerals deposited therefrom (Powell and others, 1991). Pb isotopic compositions of an ore mineral in this situation will reflect mixing of Pb sources along fluid pathways or at the site of ore deposition. Mixing of Pb sources in hydrothermal systems is a common phenomenon (Heyl and others, 1974; Richards and others, 1991; Foley and Ayuso, 1994; Kesler and others, 1994), and should be expected in the environments of sedimentary rock-hosted Au deposits of Nevada, an observation that has been confirmed by mineralogic and geochemical data (Arehart and others, 1993b; Arehart, 1996; Cline and others, 1997; Hofstra, 1997; Ilchik and Barton, 1997). The likelihood of recording fluid mixing in the sedimentary rock-hosted Au deposits using Pb isotopes is further enhanced by apparent low Pb concentrations in the hydrothermal fluids (e.g. Groff and others, 1997) and also the range of potential Pb isotopic compositions of possible igneous or sedimentary rock sources. However, unlike stable isotopic data for mixing of fluid, Pb isotopes provide an avenue to constrain which of the potential sources actually contributed Pb to the hydrothermal system, thus indirectly constraining potential sources of Au.

This paper presents initial efforts to constrain Pb sources in sedimentary rock-hosted Au deposits in northern Nevada (fig. 1). To this end, Pb isotopic compositions are reported for sulfides in sedimentary rock-hosted Au deposits at Getchell (Cline and others, 1997; stage 5 of Groff and others, 1997), Betze-Post (Ferdock and others, 1997), and in the Jerritt Canyon Mining District, which forms a part of the Independence Group (Hofstra and others, 1991). In addition, sulfides deposited during an earlier pluton-related event at the Betze-Post deposit were also analyzed (Ferdock and others, 1997) (fig. 1; table 1) in order to constrain the Pb isotopic composition of a source fluid of magmatic composition. Critical for interpreting these ore-related Pb isotopic values is the Pb isotopic compositions of potential Pb reservoirs that might have contributed Pb to a hydrothermal system. These reservoirs are: (1) Jurassic, Cretaceous, and Tertiary plutonic and volcanic rocks (Wooden and others, 1997, this volume), and (2) Early and Middle Paleozoic sedimentary rocks (table 2) that either host the deposits or are present at higher structural levels. Contributions from a third reservoir, the deeply buried Late Proterozoic and earliest Paleozoic clastic wedge not widely exposed across northern Nevada, is



**Figure 1:** Location of sedimentary rock-hosted Au deposits (filled diamonds) in northern Nevada, showing major groups and trends of these deposits. B, Betze-Post; G, Getchell; JC, Jerritt Canyon District. Geographic localities are: IM, Independence Mountains; OM, Osgood Mountains; RM, Roberts Mountains.

predicted in amagmatic models (Ilchik and Barton, 1997). As yet, no Pb isotopic data is available for these rocks, and this lack needs to be rectified to fully understand the potential roles of various source terranes in contributing Pb, and by inference Au, to the sedimentary rock-hosted deposits. Continuing work using both conventional Pb isotopic methods and spot-analyses using the Sensitive High Resolution Ion-MicroProbe (SHRIMP) will provide additional information pertinent to this issue.

## GEOLOGIC FRAMEWORK AND DEPOSIT SETTING

The geologic framework of sedimentary rock-hosted Au deposits in northern Nevada is well known (Stewart, 1980; Groff and others, 1997; Teal and Jackson, 1997). Principal host rocks for the deposits are Lower Cambrian through Devonian calcareous sedimentary rocks deposited on a westward prograding miogeoclinal shelf. The miogeoclinal rocks were tectonically buried beneath the Robert Mountains

**Table 1:** Present-day Pb isotopic compositions for sulfides from the Post-Betze, Getchell, and Jerritt Canyon sediment-hosted gold deposits, northern central Nevada.<sup>1</sup>

Sample no.	Mineral or rock type	<sup>206</sup> Pb/ <sup>204</sup> Pb	<sup>207</sup> Pb/ <sup>204</sup> Pb	<sup>208</sup> Pb/ <sup>204</sup> Pb
<b><i>Sediment-hosted Au deposit</i></b>				
<b><i>Betze-Post</i></b>				
BMV	Galena	19.635	15.753	39.287
	Pyrite	19.629	15.751	39.271
SP93-528	Pyrite	20.114	15.751	39.238
SP96-7033	Marcasite, “framboidal”	29.004	16.195	39.338
	replicate	28.872	16.186	39.354
<b><i>Getchell</i></b>				
G-7-15-3	Realgar	19.929	15.781	39.020
G92-205-1079	Orpiment	20.665	15.815	38.878
<b><i>Jerritt Canyon</i></b>				
J89-7	Orpiment	21.437	15.803	38.933
J89-8	Stibnite	19.653	15.737	39.225

<sup>1</sup> Sulfide dissolution techniques, column chromatography, and error analysis are described by Arribas and Tosdal (1994). Galena, pyrite, marcasite, and stibnite were dissolved using concentrated HNO<sub>3</sub>. Orpiment and realgar were dissolved using concentrated aqua regia. Measured Pb isotopic compositions were corrected for 0.125 percent fractionation per atomic mass unit, based upon replicate analyses of the National Bureau of Standards 981 and 982. Laboratory procedural blanks were 1 ng Pb or less and the precision of the isotopic measurements was generally better than 0.05 percent at the 2 sigma confidence level. Lead isotope compositions are reproducible to the ±0.8, ±0.1, and ±0.14 percent (2 sigma), respectively, for <sup>206</sup>Pb/<sup>204</sup>Pb, <sup>207</sup>Pb/<sup>204</sup>Pb, and <sup>208</sup>Pb/<sup>204</sup>Pb.

thrust system during the Devonian and early Mississippian Antler orogeny. Upper-plate rocks of the Antler allochthon consist of Ordovician eugeoclinal, fine-grained siliceous clastic rocks and chert deposited in deep water farther west from the craton. They represent the westward time-stratigraphic equivalents of the calcareous miogeoclinal rocks (Poole and others, 1992). The siliciclastic eugeoclinal rocks generally are not good hosts to ore, although some deposits are known in these rocks (Teal and Jackson, 1997). Less common host rocks in the sedimentary rock-hosted deposits are Mississippian carbonate-rich rocks deposited in the clastic wedge shed eastward as an overlap assemblage during and after emplacement of the Antler allochthon. Younger contractile deformation in the Pennsylvanian, early Triassic, and Early Cretaceous superposed additional structural and stratigraphic complexities to the vicinity of the deposits. Stocks and dikes were emplaced into structurally interleaved Paleozoic rocks in the Jurassic, Cretaceous, and Eocene, and several deposits are spatially related to their margins.

The Getchell deposit in the Osgood Mountains (fig. 1) is the westernmost sedimentary rock-hosted Au deposit from which Pb isotopic data are reported herein. This deposit is located along the flank of a Cretaceous granodioritic stock that intruded and thermally metamorphosed fine-grained calcareous rocks of the Lower Cambrian Preble and Ordovician Comus Formations (Cline and others, 1997; Groff and others,

1997). Gold ore is hosted principally in interbedded limestone and shale of the Preble Formation.

The Betze-Post deposit in the Carlin trend (fig. 1) is the largest Au deposit in Nevada (Leonardson and Rahn, 1996; Ferdock and others, 1997). Here, Au is hosted in altered miogeoclinal calcareous rocks of the Silurian and Devonian Roberts Mountains Formation, Devonian Popovich Formation, and overlying informally named Rodeo Creek unit. These rocks were structurally buried beneath eugeoclinal siliciclastic rocks and chert of the Ordovician Vinini Formation along the Roberts Mountains thrust. The structural sequence was intruded by the late Middle Jurassic Goldstrike granodioritic to dioritic stock and by Eocene and Oligocene quartz monzonite and monzonite dikes (Arehart and others, 1993a; Emsbo and others, 1996). Polyphase sulfide deposition characterizes the deposit. The oldest sulfide stage in the deposit is represented by quartz-sericite-pyrite-base metal veins associated with intrusion of the Middle Jurassic Goldstrike stock (Ferdock and others, 1997). These veins, from which galena and pyrite were analyzed, predate the main stage of gold deposition, although minor gold is associated with the veins. Pyrite also grew as part of the metamorphic minerals in thermally metamorphosed wall rocks surrounding the stock. Main stage gold deposition was superposed on the older sulfide depositional events.

The Jerritt Canyon Mining District in the Independence

**Table 2:** Present-day Pb isotopic compositions for lower and middle Paleozoic sedimentary rocks, north-central Nevada<sup>1</sup>.

Sample no.	Formation	Rock type	<sup>206</sup> Pb/ <sup>204</sup> Pb	<sup>207</sup> Pb/ <sup>204</sup> Pb	<sup>208</sup> Pb/ <sup>204</sup> Pb
<u>Eugeoclinal rocks</u>					
<i>Eureka Mining District</i>					
EU-2	Pogonip Group (Ordovician)	limestone with chert nodules	19.452	15.695	38.765
EU-4	Windfall Fm.(Cambrian)	limestone	19.604	15.686	38.797
<i>Roberts Mountains</i>					
RM-4	upper Vinini Fm. (Ordovician)	chert and shale sandy chert	19.680	15.668	38.571
RM-11			27.563	16.166	38.852
RM-24	upper Vinini (?) Fm.	shale	21.700	15.856	38.691
<i>Northern Independence Range</i>					
Valmy Group (late Cambrian to Middle Ordovician)					
NI-47	McAfee quartzite <sup>2</sup>	shaley argillite	18.879	15.671	38.431
NI-17		shale/siltstone	19.734	15.714	39.323
NI-48	rocks of Jack's Peak <sup>2</sup> Snow Canyon Fm. (Ordovician)	argillite, shale, chert	18.871	15.612	38.407
NI-3	Lower	shale	19.422	15.709	39.524
NI-6		claystone	21.473	15.833	38.568
NI-9		shaley mudstone	18.477	15.589	38.648
NI-10		sandstone	20.761	15.745	39.192
NI-12		shale	21.542	15.785	38.806
NI-15		shale and silstone	20.425	15.718	38.907
NI-54	Upper	siltstone	18.952	15.632	39.027
NI-55		shaley mudstone	25.321	16.019	38.618
NI-58		sandstone/shale	20.336	15.708	38.741
NI-61a		shale	18.386	15.569	38.470
NI-63		shale/siltstone	19.754	15.661	39.501
NI-71		shale/argillite	19.275	15.643	38.147
<u>Miogeoclinal rocks</u>					
NI-26	Roberts Mtn. Fm.	silty limestone	20.704	15.666	39.024
NI-27	(Silurian-Devonian)	limestone	19.794	15.651	39.033
NI-76	Hansen Creek Fm.	chert-limestone	22.743	15.780	38.654
NI-79	(Ordovician-Silurian)	limestone	18.130	15.571	37.560
NI-82		shaley limestone	20.015	15.715	38.956

<sup>1</sup> Whole-rock dissolution techniques, column chromatography, and error analysis are described by Arribas and Tosdal (1994). Measured Pb isotopic compositions were corrected for 0.125 percent fractionation per atomic mass unit, based upon replicate analyses of the National Bureau of Standards 981 and 982. Laboratory procedural blanks were 1 ng Pb or less and the precision of the isotopic measurements was generally better than 0.05 percent at the 2 sigma confidence level. Lead isotope compositions are reproducible to the  $\pm 0.8$ ,  $\pm 0.1$ , and  $\pm 0.14$  percent (2 sigma), respectively, for <sup>206</sup>Pb/<sup>204</sup>Pb, <sup>207</sup>Pb/<sup>204</sup>Pb, and <sup>208</sup>Pb/<sup>204</sup>Pb.

<sup>2</sup> The informal units, the McAfee quartzite and rocks of Jack's Peak, are stratigraphic designations restricted to the Independence Mountains. These units form part of the uppermost Ordovician Valmy Group at higher stratigraphic levels than the Snow Canyon Formation (D.T. Wilton, 1998, oral commun.)

Mountains (fig. 1) consists of several sedimentary rock-hosted Au deposits hosted in miogeoclinal calcareous rocks of the Ordovician and Silurian Hansen Creek Formation and overlying Silurian and Devonian Roberts Mountains Formation (Hofstra and others, 1991). Eugeoclinal siliciclastic rocks and chert of the Ordovician Valmy Group, including the Snow Canyon Formation and stratigraphically higher informal units known as the McAfee quartzite and rocks of Jack's Peak, structurally overlie the miogeoclinal calcareous rocks along the Roberts Mountains thrust system. Gold deposition is

interpreted to have occurred in the Eocene or early Oligocene (Hofstra, 1995).

## Pb ISOTOPIC DATA FRAMEWORK IGNEOUS ROCKS

Pb isotopic compositions of intermediate and silicic plutonic and volcanic rocks emplaced through continental crust generally reflect the isotopic composition of crustal

environments (Davidson, 1996). Wooden and others (1997, this volume) noted large-scale geographic variations in Pb isotopic compositions of Mesozoic and Tertiary igneous rocks across northern Nevada and adjoining California and Utah. They, furthermore, argue that these Pb isotopic variations reflect compositional changes in the lower and middle crust and that they were established during continental rifting in the late Proterozoic and early Paleozoic (see also Tosdal and Wooden, 1997).

Three Pb isotopic provinces across northern Nevada were defined based on Pb isotopic compositions (fig. 1) (Wooden and others, 1997, this volume). These provinces, the western, central, and eastern Pb Provinces, form north-northwesterly trending crustal domains in central Nevada. The western Pb Province, unlike the other two, is more areally extensive, underlying most of western and northern Nevada where it cuts at high angles across the central and eastern Pb Provinces (fig. 1). Within the western and central Pb Province, Pb isotopic compositions of igneous rocks show regular eastward variations with geographic location (Wooden and others, this volume). The transition from the western to the central Pb Province is marked by a small but noticeable step increase in  $^{208}\text{Pb}/^{204}\text{Pb}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  at  $^{206}\text{Pb}/^{204}\text{Pb}=19.1$ . The eastward Pb isotopic variations across these province reflects increasing incorporation of crustal material in the igneous rocks, and the accompanying masking of any "mantle" signature in the magmas. This regular pattern changes at the boundary with the eastern Pb Province, or along the Carlin Trend, to the east of which no regular Pb isotopic pattern is discernible and there is a wide range of Pb isotopic compositions (Wooden and others, this volume). The most notable change here is the sudden increase in  $^{208}\text{Pb}/^{204}\text{Pb}$  ( $>39.7$ ) in Mesozoic plutons as well as a very large range in  $^{206}\text{Pb}/^{204}\text{Pb}$  between 17 and 20 with a correspondingly high  $^{208}\text{Pb}/^{204}\text{Pb}>37.5$  in Tertiary volcanic and plutonic rocks (fig. 2). These Pb isotopic compositions reflect the heterogeneous nature of the Archean crust, on the north, and Proterozoic crust, on the south (Zartman, 1974; Wright and Wooden, 1991; Wright and Snoke, 1993; Farmer and Ball, 1997; Wooden and others, 1997, this volume). Because of the regular Pb isotopic variations across the central Pb Province where most of the sedimentary rock-hosted Au deposits are located, the narrow Pb isotopic compositional range of any pluton that is potentially genetically related to a sedimentary rock-hosted Au deposit is predictable, if the data are not available.

Deposits for which sulfides were analyzed for their Pb isotopic compositions reported herein are scattered across northern Nevada. The westernmost is the Getchell deposit, which lies along the boundary between the western and central Pb Provinces (fig. 1), or at the edge of the thinned Precambrian crust. The Betze-Post deposit located along the Carlin trend lies along the boundary between the central and eastern Pb Provinces (fig. 1). The Jerritt Canyon Mining District lies close to the transition between the eastern or central Pb

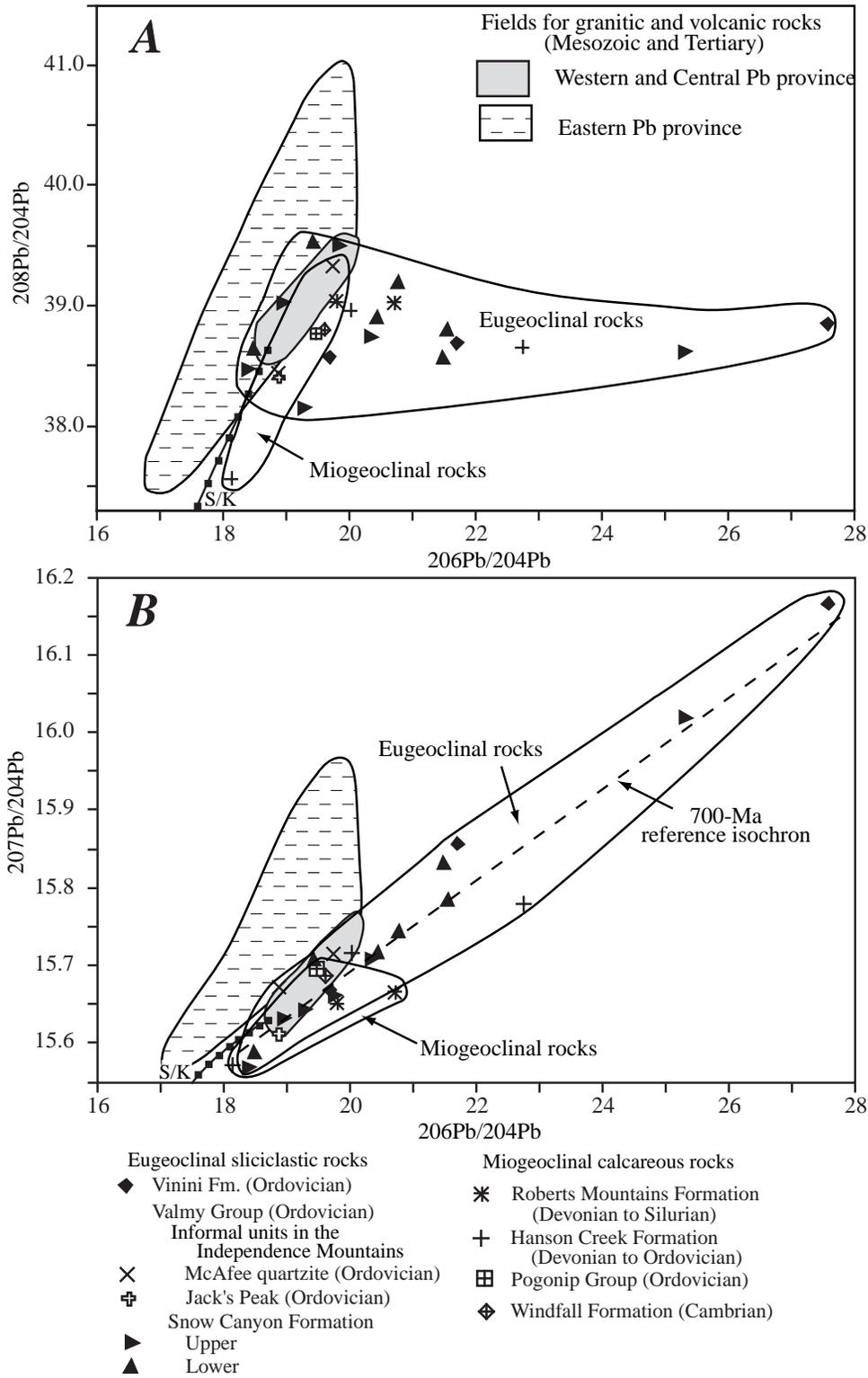
Province and the western Pb Province (fig. 1). These deposits lie west of relatively intact Precambrian basement, as also suggested by Cunningham (1988).

## SEDIMENTARY ROCKS

Present-day whole-rock Pb isotopic compositions are reported for twenty-seven Paleozoic sedimentary rocks from the Independence Mountains, Roberts Mountains, and from the Eureka area in northeastern Nevada (fig. 1; table 2). These samples include most major rock units and rock types present in the region of the sedimentary rock-hosted Au deposits along the Carlin trend and in the Independence Group (fig. 1). Notable exceptions are samples from the Popovich Formation and Rodeo Creek unit, which are the primary hosts for the deposits in the northern Carlin trend (Teal and Jackson, 1997). In addition, no Pb isotopic data are available for Cambrian and Ordovician sedimentary rocks hosting sedimentary-rock-hosted deposits in the Osgood Mountains in north-central Nevada. However, as Paleozoic detritus was derived principally from the east (Stewart, 1980; Poole and others, 1992; Gehrels and Dickinson, 1995), Pb isotopic compositions of Cambrian and Ordovician sedimentary rocks in the Osgood Mountains are likely to be similar to those determined for rocks farther east. A similar argument applies to the Popovich Formation and Rodeo Creek unit. Nonetheless, this assumption must be confirmed. Lastly, before a complete view of the Pb sources in the sedimentary rock-hosted can be established, Pb isotopic compositions of late Proterozoic and earliest Paleozoic clastic rocks not exposed near the deposits also need to be determined.

Pb isotopic compositions of eugeoclinal and miogeoclinal rocks plot as partly overlapping fields consistent with their in part common source regions and sedimentologic evidence (fig. 2). There is a considerable range in present-day Pb isotopic compositions, with  $^{206}\text{Pb}/^{204}\text{Pb}$  ranging from 18.1 to 25.3 and a sympathetic range of  $^{207}\text{Pb}/^{204}\text{Pb}$  between 15.57 and 16.0 (table 2; fig. 2b). Within this range, miogeoclinal calcareous rocks have low  $^{206}\text{Pb}/^{204}\text{Pb}$  whereas the Pb isotopic compositions of eugeoclinal siliciclastic rocks span nearly the entire range of  $^{206}\text{Pb}/^{204}\text{Pb}$ . On the  $^{207}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  evolution diagram (fig. 2b), the eugeoclinal and miogeoclinal rocks scatters about a 700-Ma reference isochron defined by siliciclastic rocks of the Snow Canyon Formation. This 700-Ma reference isochron has no chronologic significance for these Paleozoic rocks but suggests some heterogeneity of initial Pb isotopic compositions of the fine-grained clastic rocks. It also emphasizes the influence of Precambrian craton detritus in these rocks.

A Pb isotopic distinction between miogeoclinal and eugeoclinal sedimentary rocks is particularly evident in the  $^{208}\text{Pb}/^{204}\text{Pb}$  values (fig. 2a). Calcareous miogeoclinal rocks form a field that lies slightly below but parallel to the average



**Figure 2:** Pb isotopic compositions of potential Pb sources in sedimentary-rock-hosted Au deposits in northern Nevada. (A)  $^{208}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  and (B)  $^{207}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  evolution diagrams. Fields for the Pb isotopic provinces is from Wooden and others (1997; this volume and references therein). Rocks of Jack's Peak and the McAfee quartzite are informal units found at high stratigraphic levels in the Ordovician Valmy Group only in the Independence Mountains (D.T. Wilton, 1998 oral commun.). S/K, average crustal growth curve of Stacey and Kramers (1975).

crustal growth curve of Stacey and Kramers (1975). This suggests a Th/U value close to average crust, or about 4. In contrast,  $^{208}\text{Pb}/^{204}\text{Pb}$  values of eugeoclinal siliciclastic rocks vary over a narrow range between 38.1 and 39.5 despite a large range in  $^{206}\text{Pb}/^{204}\text{Pb}$  between 18.3 and 25.3 (table 2; fig. 2A). Pb isotopic compositions of the eugeoclinal rocks plot in a field that overlaps the average crustal growth curve and the higher  $^{208}\text{Pb}/^{204}\text{Pb}$  part of the miogeoclinal rock field, but more importantly the eugeoclinal rock field extends outward toward higher  $^{206}\text{Pb}/^{204}\text{Pb}$  over the limited range of  $^{208}\text{Pb}/^{204}\text{Pb}$ . The limited range of  $^{208}\text{Pb}/^{204}\text{Pb}$  in eugeoclinal rocks requires highly variable but generally low Th/U values less than the average crustal value of about 4. Time-integrated growth since deposition accounts for the variability in the  $^{206}\text{Pb}/^{204}\text{Pb}$ .

There are several explanations for the low but variable Th/U values in the siliciclastic eugeoclinal rocks. An increasing percentage of limestone can produce variable and low Th/U in sedimentary rocks (Rye and others, 1974; Goldhaber and others, 1995 and references therein). However, this explanation is untenable for the eugeoclinal siltstone, sandstone, and chert, as these rocks lack significant carbonate material in contrast to the dominantly calcareous miogeoclinal rocks. Island arc rocks and oceanic rift basalts represent two other environments where rocks can have low Th/U values (Tatsumoto, 1978; Allègre and others, 1986). Conceivably, detritus from these environments known to have been present along the coast of North America in the Paleozoic (Miller and others, 1992; Poole and others, 1992) could impart low Th/U values to the eugeoclinal rocks. In this scenario, variable Th/U values in the siliciclastic eugeoclinal rocks resulted from mixtures of detritus from different geologic environments. One clastic source was characterized by Th/U ~ 4, like the one contributing to the miogeoclinal rocks, that was shed from the craton to the east. A second clastic source was derived from fringing volcanic oceanic island arcs and back-arcs. Abundant phosphorite and organic matter are two other sedimentary environments where low Th/U values can be established (Kesler et al, 1994). Both characterize the Paleozoic clastic sequences particularly miogeoclinal rocks in northern Nevada. Just what is the explanation for the low Th/U trends is not known, but the tendency toward low Th/U is a distinctive attribute of the eugeoclinal sedimentary rocks. It reflects time-integrated growth since deposition in the Paleozoic, any modification of the Pb isotopic compositions during diagenesis in the Paleozoic, and subsequent low-grade regional metamorphism, plutonism, and hydrothermal circulation in the Mesozoic and Tertiary (Arehart and others, 1993a; Phinsey and others, 1996; Ferdock and others, 1997; Groff and others, 1997).

At low values of  $^{206}\text{Pb}/^{204}\text{Pb}$ , eugeoclinal and miogeoclinal sedimentary rocks overlap the field for igneous rock in the central Pb Provinces, but only a limited part of the field for the eastern Pb province.

## ORE MINERALS

Au in sedimentary rock-hosted Au deposits is present in arsenian-rich rims on pyrite or as small arsenian pyrite grains in a siliceous groundmass (Arehart and others, 1993c; Cline and others, 1997; Ferdock and others, 1997). While pyritiferous rocks are abundant in the deposits, the complex relationship between ore-related arsenian pyrite and older non-ore pyrite precludes analyzing those minerals in bulk for their Pb isotopic compositions. Microanalytical techniques, in progress, are required to obtain Pb isotopic compositions of these complex minerals. Instead, other sulfide minerals, such as orpiment, realgar, and stibnite, that were deposited during the waning stage of hydrothermal activity (Cline and others, 1997; Ferdock and others, 1997) serve as proxies. Their Pb isotopic compositions can be analyzed using bulk mineral samples (see table 1 for analytical data and techniques). Some orpiment and realgar contain micro-inclusions of auriferous arsenian pyrite (Simon and others, 1997), hence any Pb isotopic composition of these minerals provides indirect constraints on Pb isotopic compositions of the hydrothermal fluid.

During this initial survey, Pb isotopic compositions were determined from eight sulfide minerals from seven samples (table 1). Four sulfide samples were of orpiment, realgar, marcasite, and stibnite formed as part of the paragenetic sequence at the Getchell deposit and in the Jerritt Canyon Mining District. Attempts to analyze orpiment, realgar, and stibnite from the Betze-Post deposit failed due to the lack of measurable Pb in these minerals. Similar results were obtained from orpiment and realgar from Getchell and Jerritt Canyon Mining District. Failure to detect Pb during analysis of realgar from Getchell using the SHRIMP confirms the low to negligible Pb contents of at least this sulfide mineral (R.M. Tosdal, 1997 unpublished data). From the Betze-Post deposit, Pb isotopic compositions were also determined on galena and pyrite (sample BMV, table 1) from one of the quartz-sericite-pyrite-base metal veins cutting the Goldstrike stock, and from pyrite (sample SP93-528, table 1) in thermally metamorphosed rocks adjacent to the stock. As sulfides in the quartz-sericite-pyrite veins are related to the stock, their Pb isotopic compositions record the magmatic-derived hydrothermal fluids. The paragenesis of pyrite in the hornfels aureole is enigmatic, as the pyritiferous whole-rock contains elevated arsenic concentrations typical of a sedimentary rock-hosted Au deposit, but also has low Au concentrations. The last sulfide from Betze-Post is from a 2 cm-in-diameter "framoid-like" marcasite (sample SP96-7033, table 1) interpreted to be a late hydrothermal mineral in the fringes of the deposit (S.G. Peters, 1996 unpublished data).

Pb isotopic compositions of sulfides regardless of paragenesis and location overlap the field for plutonic rocks from the eastern part of the central Pb Province (the higher  $^{206}\text{Pb}/^{204}\text{Pb}$  portion of the field for the western and central Pb

provinces on fig. 3), but largely plot at higher  $^{206}\text{Pb}/^{204}\text{Pb}$  values outside the field for igneous rocks from the eastern Pb Province. Sulfide Pb isotopic compositions also overlap the fields for miogeoclinal and eugeoclinal sedimentary rocks on the  $^{208}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram (fig. 3A), but plot for the most part at higher  $^{207}\text{Pb}/^{204}\text{Pb}$  at a given  $^{206}\text{Pb}/^{204}\text{Pb}$  than do the miogeoclinal sedimentary rocks (fig. 3B). Orpiment and realgar from Getchell, located at the transition between the western and central Pb Province, have Pb isotopic compositions noticeably higher ( $^{208}\text{Pb}/^{204}\text{Pb} > 39.020$ ;  $^{206}\text{Pb}/^{204}\text{Pb} > 15.781$ ;  $^{206}\text{Pb}/^{204}\text{Pb} > 19.929$ ; table 1) than those known for the Cretaceous Osgood Mountains stock (Pb isotopic compositions of K-feldspar:  $^{208}\text{Pb}/^{204}\text{Pb} = 38.867$ ;  $^{207}\text{Pb}/^{204}\text{Pb} = 15.685$ ;  $^{206}\text{Pb}/^{204}\text{Pb} = 19.073$ ) (J.L. Wooden, 1996 unpublished data), the nearest igneous rocks; these granodioritic rocks were not genetically linked to the Au deposit (Groff and others, 1997) but they would represent approximate Pb isotopic compositions of magmatically derived Pb in this part of Nevada. In contrast, galena and pyrite from an igneous-related quartz-sericite-pyrite vein within the Goldstrike stock plot within the appropriate part of the field for the central Pb isotopic province that is consistent with their geographic positions. Pyrite from the hornfels aureole to the Goldstrike stock has similar  $^{208}\text{Pb}/^{204}\text{Pb}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  values as the igneous-related sulfides but has a higher  $^{206}\text{Pb}/^{204}\text{Pb}$  values more typical of the miogeoclinal and eugeoclinal sedimentary rocks.

Igneous-related sulfides from the Betze-Post deposit seem to anchor the lower  $^{206}\text{Pb}/^{204}\text{Pb}$  end of a diffuse sulfide array (fig. 3). Sulfides from the sedimentary rock-hosted Au deposits, except for a stibnite from the Jerritt Canyon Mining District, plot at higher  $^{206}\text{Pb}/^{204}\text{Pb}$  values along this diffuse array that is anchored at the high  $^{206}\text{Pb}/^{204}\text{Pb}$  end by late(?) marcasite from the Betze-Post deposit. The marcasite has very high  $^{206}\text{Pb}/^{204}\text{Pb}$  (average=28.9) and  $^{207}\text{Pb}/^{204}\text{Pb}$  (average=16.19) but a correspondingly low  $^{208}\text{Pb}/^{204}\text{Pb}$  (38.9-39.2). With increasing  $^{206}\text{Pb}/^{204}\text{Pb}$  values, sulfides from the sedimentary-rock-hosted Au deposits have Pb isotopic compositions that diverge from the fields for miogeoclinal rocks (fig. 3B). They do, however, lie completely within the field defined for Paleozoic eugeoclinal rocks on the  $^{208}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram (fig. 3A). A similar tendency is shown on the  $^{207}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  diagram, except for the sulfides from Getchell which plot above the field for the eugeoclinal rocks (fig. 3B). Clearly, the available Pb isotopic composition of sulfides are more similar to those of the eugeoclinal rocks than to miogeoclinal rocks.

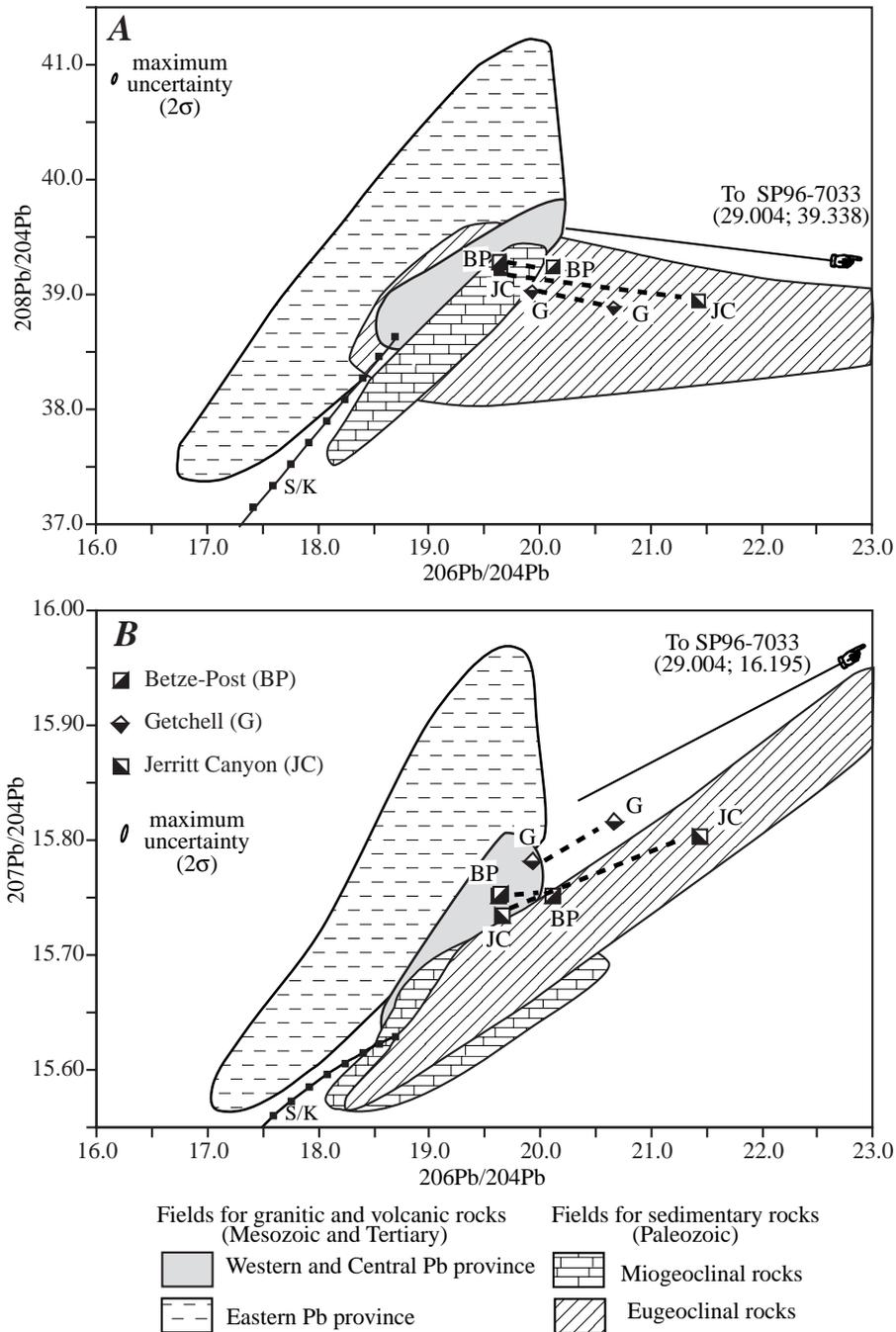
### PRELIMINARY CONSTRAINTS OF Pb SOURCES IN THE SEDIMENT-HOST AU DEPOSITS

Limited Pb isotopic data from sulfides in the Getchell

deposits and in the Jerritt Canyon Mining District provide preliminary constraints on Pb sources in sedimentary rock-hosted Au deposits. Based on the data available, Pb in the deposits seemingly reflects mixing of Pb isotopic sources, a conclusion that is consistent with other fluid constraints (summarized by Arehart, 1996). One end member is a lower  $^{206}\text{Pb}/^{204}\text{Pb}$  source characterized by Th/U and U/Pb values similar to igneous rocks present in the western and central Pb Province. The other end member or higher  $^{206}\text{Pb}/^{204}\text{Pb}$  source is characterized by low but variable Th/U and elevated U/Pb like that present in the siliciclastic eugeoclinal rocks. Local contribution of Pb from calcareous miogeoclinal rocks hosting the deposits seemingly is precluded by two observations. One observation is that Pb isotopic compositions of orpiment, realgar, and stibnite from sedimentary-rock-hosted deposits lie at consistently higher  $^{207}\text{Pb}/^{204}\text{Pb}$  for a given  $^{206}\text{Pb}/^{204}\text{Pb}$  than do the calcareous miogeoclinal rocks. Two, the tendency of the Pb isotopic compositions of gold-ore-related sulfides to vary within (fig. 3A) or toward (fig. 3B) the field for eugeoclinal siliciclastic rocks, argues that these rocks, or rocks of similar Pb isotopic composition, provided one component of Pb in these deposits. This conclusion confirms the suggestion of Young-Mitchell and Titley (1996) whereby the relative Au-enrichment in eugeoclinal siliciclastic rocks makes them an attractive Au source. Unfortunately, the lack of Pb isotopic data for other potential sedimentary sources of Pb (see above) makes this hypothesis tentative until the appropriate Pb isotopic data is available. As the gold-ore-related sulfides mimic the tendency to low and variable Th/U of the eugeoclinal rock, we can also infer that the sulfides are relatively young.

The nature of the lower  $^{206}\text{Pb}/^{204}\text{Pb}$  source in the gold-ore-related sulfides is at present speculative. As the mixing trends in the sulfides seems to be anchored in the Pb isotopic compositions of central Pb Province igneous rocks, a magmatic source is possible. However, derivation of this component of Pb from magmas suffers from two observations. One is the observation that the high  $^{206}\text{Pb}/^{204}\text{Pb}$  mixing component in the sedimentary rock-hosted sulfides is not the host calcareous sedimentary rocks as would be expected in a simple magmatic-hydrothermal model where mixing is between a magmatic fluid and local country rocks. Rather, rocks more similar to the siliciclastic eugeoclinal rocks, which lie at high structural level, provided the sedimentary-rock Pb component. The second observation is that Pb in the Getchell sulfides are too radiogenic in terms of  $^{207}\text{Pb}/^{204}\text{Pb}$  and  $^{208}\text{Pb}/^{204}\text{Pb}$  to have been derived from igneous rocks in that part of Nevada (see above), and then mixed with Pb from the low but variable Th/U source. It is also important to emphasize that neither of these observations absolutely precludes Pb contribution from a magma.

Alternatively, it is possible that an unknown source containing the appropriately elevated  $^{207}\text{Pb}/^{204}\text{Pb}$  values contributed the lower  $^{206}\text{Pb}/^{204}\text{Pb}$  source. This source could be other sedimentary rocks at depth, perhaps of late Proterozoic and earliest Cambrian age, that contain detritus from Archean



**Figure 3:** (A)  $^{208}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  and (B)  $^{207}\text{Pb}/^{204}\text{Pb}$  versus  $^{206}\text{Pb}/^{204}\text{Pb}$  evolution diagrams comparing Pb isotopic compositions of ore minerals from Getchell and Betze-Post deposits and from the Jerritt Canyon Mining District to potential sources of Pb in these minerals. Heavy dashed tie lines connect samples from the same deposit or mining district. S/K, average crustal growth curve of Stacey and Kramers (1975). B, Betze-Post; G, Getchell; JC, Jerritt Canyon Mining District.

rocks, such as the Wyoming Province (Wooden and Mueller, 1988; Farmer and Ball, 1997) or from a cratonic region even farther to the north (Gehrels and others, 1995). Conversely, this source could have been in the deep crust and have been fluids in Pb isotopic equilibrium with the thinned cratonic basement that underlies the late Proterozoic and Paleozoic

clastic sequences in the central Pb Province. These rocks are also inferred to have contributed Pb to the granitic magmas that intruded the crust (Wooden and others, 1997, this volume). We cannot discriminate between these possibility at this time.

Mixing of two Pb isotopic sources during evolution of the hydrothermal systems presumably took place near or at

the site of ore deposition in order to maintain their isotopic distinctions. Fluid mixing in sedimentary-rock-hosted deposits are common phenomenon and may include mixing of magmatic and sedimentary rock Pb during convective circulation around a cooling stock (Richards and others, 1991), or mixing at the site of ore deposition of basinal fluids traveling through different aquifers (Goldhaber and others, 1995). For the case of sedimentary-rock-hosted Au-Ag deposits in northern Nevada, identification of both Pb components in this mixing model awaits much additional data. However, it is certain that at least one component of Pb is derived from sedimentary rocks similar in Pb isotopic composition to the relatively Au-enriched eugeoclinal rocks (Young-Mitchell and Titley, 1996). Whether these rocks provided Pb to the waning stages of the hydrothermal system via descending circulating meteoric water (Kuehn and Rose, 1995) or via flowing fluids from reservoir rocks at depth or laterally is not known.

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